

# **UNIT 1**

## **FUNDAMENTALS OF METEOROLOGY**

### **FOREWORD**

Meteorology is the study of atmospheric phenomena. This study consists of physics, chemistry, and dynamics of the atmosphere. It also includes many of the direct effects the atmosphere has upon Earth's surface, the oceans, and life in general. The goals often ascribed to meteorology are the complete understanding and accurate prediction of atmospheric phenomena.

Meteorology may be subdivided into a large number of specialized sciences. These specialized sciences will be covered in depth in Unit 6.

The treatment of meteorology in this manual progresses from the overall fundamentals of meteorology to a thorough description of atmospheric physics and circulation, air masses, fronts, and meteorological elements. This information supplies the necessary background for you to understand chart analysis, tropical analysis, satellite analysis, and chart interpretation. With this knowledge you can become a confident, well-informed weather analyst, interpreter, and briefer.

This first unit covers the following lessons: Lesson 1, Systems of Measurement; Lesson 2, Earth-Sun Relationship; Lesson 3, Pressure; Lesson 4, Temperature; and Lesson 5, Moisture.



# UNIT 1—LESSON 1

## SYSTEM OF MEASUREMENT

### OVERVIEW

Recognize how the Metric System and the English System are used in meteorology.

### OUTLINE

Metric System

English System

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### SYSTEM OF MEASUREMENT

To work in the field of meteorology, you must have a basic understanding of the science of measurement (metrology). When you can measure what you are talking about and express it in numerical values, you then have a knowledge of your subject. To measure how far something is moved, or how heavy it is, or how fast it travels, you may use a specific measurement system. There are many such systems throughout the world today. The Metric System (CGS, centimeter-gram-second) has been recognized for use in science and research. Therefore, that system is discussed in the paragraphs that follow, with brief points of comparison to the English System (FPS, foot-pound-second).

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**Learning Objective: Recognize the units of measure used in the Metric System and the English System and how these systems of measurement are used in Meteorology.**

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The metric system is easy to learn as it is based on decimals. Because metrics are widely used in the field of meteorology, they are used throughout the manual. An introduction to metrics is presented in this unit. For a more detailed discussion of metrics, you should refer to OCC-ECC, *The Metric System*, NAVEDTRA 475-01-00-79.

As you saw earlier, the metric system uses centimeter-gram-seconds (CGS) to describe physical events. These units measure length, weight, and time, respectively. The derivation of those units are described briefly.

### LENGTH

To familiarize you with the conventional units of metric length, start with the meter.

The meter is slightly larger than the English yard (39.36 inches vs 36 inches). Prefixes are used in conjunction with the meter to denote smaller or larger units of the meter. Each larger unit is ten times larger than the next smaller unit. (See table 1-1-1.)

**Table 1-1-1.—Common prefixes used in the Metric System**

Prefix <sup>1</sup>	Symbol	Decimal Value	Scientific Notation
Kilo	K	1000	10 <sup>3</sup>
Hecto	H	100	10 <sup>2</sup>
Deka	D	10	10 <sup>1</sup>
Deci	d	.1	10 <sup>-1</sup>
Centi	c	.01	10 <sup>-2</sup>
Milli	m	.001	10 <sup>-3</sup>

<sup>1</sup>These prefixes are used with all metric units such as meters, grams, liters, and seconds (eg., kilometers, hectometers, centiliters, milliseconds).

Since the C in CGS represents centimeters (cm) you should see from table 1-1-1 that the centimeter is one-hundredth of a meter, .01M, or  $10^{-2}$  M. Conversely, 1 M equals 100 cm.

To describe a gram, the G in the CGS system, you must first have a familiarization with area and volume.

## AREA AND VOLUME

A square has four equal sides and it is a one-plane figure-like a sheet of paper. To determine how much surface area is enclosed within the square you multiply the length of one side by the length of the other equal side. If the sides were 1 centimeter (cm) in length the area of the square would be  $1\text{ cm} \times 1\text{ cm} = 1\text{ square cm}$ , or  $1\text{ cm}^2$ .

Now, if squares having an area of  $1\text{ cm}^2$  were stacked on top of each other until the stack was 1 cm tall, you would end up with a cube whose sides were each 1 cm in length. To determine the volume of the cube you simply multiply the length by the width and height. Because each side is 1 cm you end up with a volume of 1 cubic centimeter ( $\text{cm}^3$ ) ( $1\text{ cm} \times 1\text{ cm} \times 1\text{ cm} = 1\text{ cm}^3$ ). More simply stated, multiply the area of one side of the cube by the height of the cube. Once you understand how the volume of a cube is determined, you are now ready to review the G in the CGS system.

## WEIGHT

The conventional unit of weight in the metric system is the gram (gm). You could use table 1-1-1 and substitute the word gram for meter and the symbol (gm) for the symbol (M). You would then have a table for metric weight. The gram is the weight of  $1\text{ cm}^3$  of pure water at  $4^\circ\text{C}$ . At this point it may be useful to compare the weight of an object to its mass. The weight of the  $1\text{ cm}^3$  of water is 1 gm. Weight and mass are

proportional to each other. However, the weight of the  $1\text{ cm}^3$  of water changes as you move away from the gravitational center of Earth. In space the  $1\text{ cm}^3$  of water is weightless, but it is still a mass. Mass is expressed as a function of inertia/acceleration, while weight is a function of gravitational force. When we express the movement of an object we use the terms mass and acceleration.

## TIME

Time is measured in hours, minutes, and seconds in both systems. Hence, the second need not be explained in the CGS system. With a knowledge of how the CGS system can be used to express physical entities, you now have all the background to express such things as density and force.

## DENSITY

With the previous explanation of grams and centimeters, you should be able to understand how physical factors can be measured and described. For example, density is the weight something has per unit of volume. The density of water is given as 1 gram per cubic centimeter or  $1\text{ gm/cm}^3$ . By comparison, the density of water in the English system is 62.4 pounds per cubic foot or  $62.4\text{ lb/ft}^3$ .

## FORCE

Force is measured in dynes. A dyne is the force that moves a mass of 1 gram, 1 centimeter per square second. This is commonly written as  $\text{gm cm/sec}^2$ ,  $\text{gm cm/sec/sec}$  or  $\text{gm/cm/sec}^2$ . The force necessary for a gram to be accelerated at  $980.665\text{ cm/sec}^2$  at  $45^\circ$  latitude is 980.665 dynes. For more detailed conversion factors commonly used in meteorology and oceanography, refer to *Smithsonian Meteorology Tables*.

## UNIT 1—LESSON 2

# EARTH-SUN Relationship

### OVERVIEW

Describe how the Earth-Sun relationship affects radiation and incoming solar radiation.

### OUTLINE

Sun

Earth

Radiation

Insolation

Radiation (Heat) Balance in the Atmosphere

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### EARTH-SUN RELATIONSHIP

The Sun is a great thermonuclear reactor about 93 million miles from Earth. It is the original source of energy for the atmosphere and life itself. The Sun's energy is efficiently stored on Earth in such things as oil, coal, and wood. Each of these was produced by some biological means when the Sun acted upon living organisms. Our existence depends on the Sun because without the Sun there would be no warmth on Earth, no plants to feed animal life, and no animal life to feed man.

The Sun is important in meteorology because all natural phenomena can be traced, directly or indirectly, to the energy received from the Sun. Although the Sun radiates its energy in all directions, only a small portion reaches our atmosphere. This relatively small portion of the Sun's total energy represents a large portion of the heat energy for our Earth. It is of such importance in meteorology that every Aerographer's Mate should have at least a basic knowledge about the Sun and the effects it has on Earth's weather.

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**Learning Objective: Describe how radiation and insolation are affected by the Earth-Sun relationship.**

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### SUN

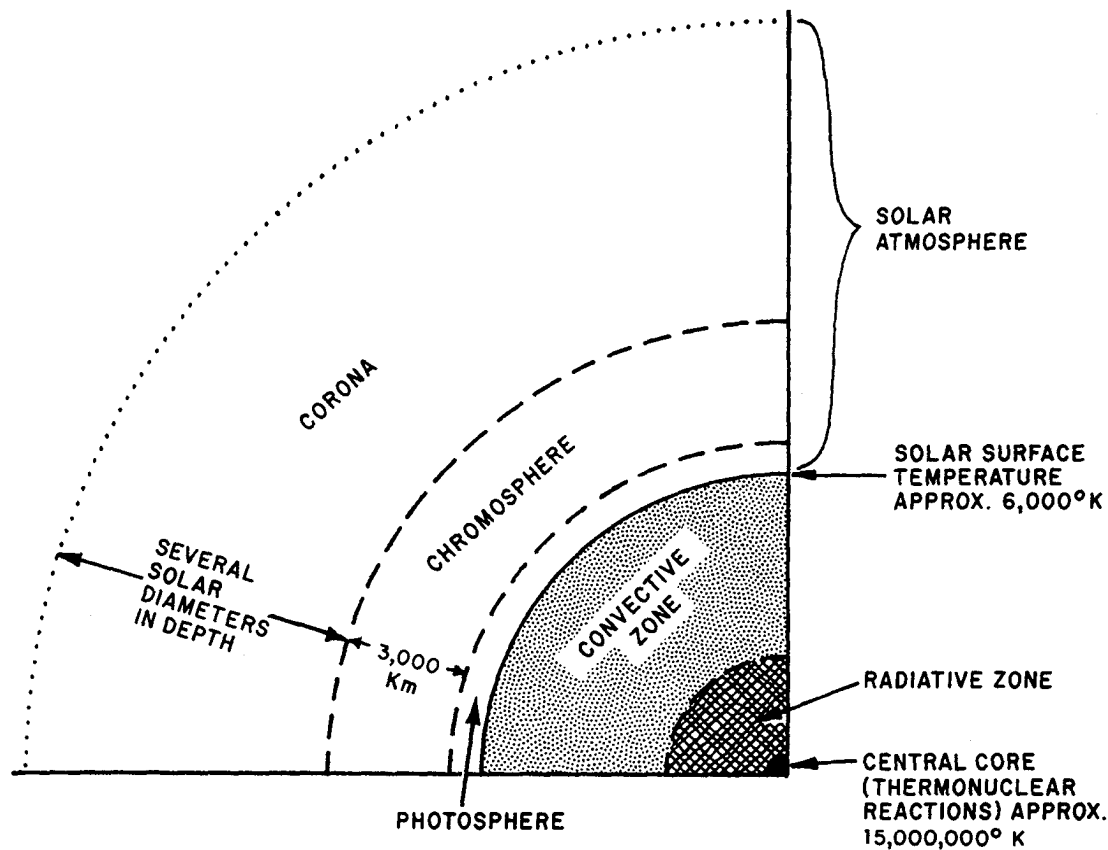
The Sun may be regarded as the only source of heat energy that is supplied to Earth's surface and the atmosphere. All weather and motions in the atmosphere are due to the energy radiated from the Sun.

The Sun's core has a temperature of 15,000,000°K and a surface temperature of about 6,000°K (10,300°F). The Sun radiates electromagnetic energy in all directions. However, Earth intercepts only a small fraction of this energy. Most of the electromagnetic energy radiated by the Sun is in the form of light waves. Only a tiny fraction is in the form of heat waves. Even so, better than 99.9 percent of Earth's heat is derived from the Sun in the form of radiant energy.

### Solar Composition

The Sun may be described as a globe of gas heated to incandescence by thermonuclear reactions from within the central core.

The main body of the Sun, although composed of gases, is opaque and has several distinct layers. (See fig. 1-2-1.) The first of these layers beyond the radiative zone is the convective zone. This zone extends very nearly to the Sun's surface. Here, heated gases are raised buoyantly upwards with some cooling occurring and subsequent convective action similar to that which occurs within Earth's atmosphere: The next layer is a



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Figure 1-2-1.—One-quarter cross-section depicting solar structure.

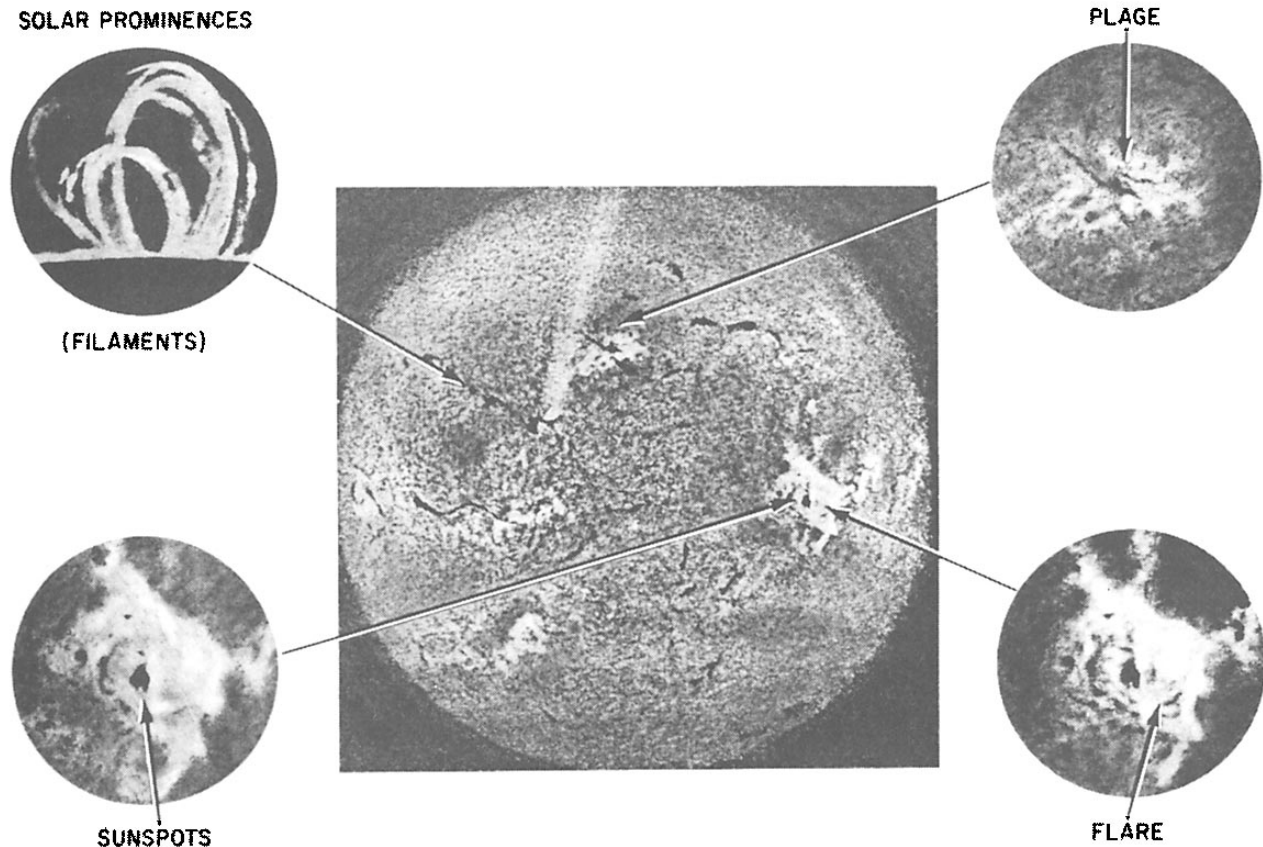
well-defined visible surface layer referred to as the photosphere. The bottom of the photosphere is the solar surface. In this layer the temperature has cooled to a surface temperature of  $6,000^{\circ}\text{K}$  at the bottom to  $4,300^{\circ}\text{K}$  at the top of the layer. All the light and heat of the Sun is radiated from the photosphere. Above the photosphere is a more transparent gaseous layer referred to as the chromosphere with a thickness of about 1,800 miles (3,000 km). It is hotter than the photosphere. Above the chromosphere is the corona, a low density high temperature region. It is extended far out into interplanetary space by the solar wind—a steady outward streaming of the coronal material. Much of the electromagnetic radiation emissions consisting of gamma rays through x-rays, ultraviolet, visible and radio waves, originate in the corona.

Within the solar atmosphere we see the occurrence of transient phenomena (referred to as solar activity), just as cyclones, frontal systems, and thunderstorms occur within the atmosphere

of Earth. This solar activity may consist of the phenomena discussed in the following paragraphs which collectively describe the features of the solar disk (the visual image of the outer surface of the sun as observed from outside regions). (See fig. 1-2-2.)

### Solar Prominences/Filaments

Solar prominences/filaments are injections of gases from the chromosphere into the corona. They appear as great clouds of gas, sometimes resting on the Sun's surface and at other times floating free with no visible connection. When viewed against the solar disk, they appear as long dark ribbons and are called filaments. When viewed against the solar limb (the dark outer edge of the solar disk), they appear bright and are called prominences. (See fig. 1-2-2.) They display a variety of shapes, sizes, and activity that defy general description. They have a fibrous structure and appear to resist solar gravity. They may



**Figure 1-2-2.—Features of the solar disk.**

extend 18,500 to 125,000 miles (30,000 to 200,000 km) above the chromosphere. The more active types have temperatures of 10,000°K or more and appear hotter than the surrounding atmosphere.

### **Sunspots**

Sunspots are regions of strong localized magnetic fields and indicate relatively cool areas in the photosphere. They appear darker than their surroundings and may appear singly or in more complicated groups dominated by larger spots near the center. (See fig. 1-2-2.)

Sunspots begin as small dark areas known as pores. These pores develop into full-fledged spots in a few days, with maximum development occurring in about 1 to 2 weeks. When sunspots decay the spot shrinks in size and its magnetic field also decreases in size. This life cycle may consist of a few days for small spots to near 100 days for larger groups. The

larger spots normally measure about 94,500 miles (120,000 km) across. Sunspots appear to have cyclic variations in intensity, varying through a period of about 8 to 17 years. Variation in number and size occurs throughout the sunspot cycle. As a cycle commences, a few spots are observed at high latitudes of both solar hemispheres, and the spots increase in size and number. They gradually drift equatorward as the cycle progresses, and the intensity of the spots reach a maximum in about 4 years. After this period, decay sets in and near the end of the cycle only a few spots are left in the lower latitudes (50 to 100).

### **Plages**

Plages are large irregular bright patches that surround sunspot groups. (See fig. 1-2-2.) They normally appear in conjunction with solar prominences or filaments and may be systematically arranged in radial or spiral patterns. Plages

are features of the lower chromosphere and often completely or partially obscure an underlying sunspot.

## Flares

Solar flares are perhaps the most spectacular of the eruptive features associated with solar activity. (See fig. 1-2-2.) They look like flecks of light that suddenly appear near activity centers and come on instantaneously as though a switch were thrown. They rise sharply to peak brightness in a few minutes, then decline more gradually. The number of flares may increase rapidly over an area of activity. Small flarelike brightening are always in progress during the more active phase of activity centers. In some instances flares may take the form of prominences, violently ejecting material into the solar atmosphere and breaking into smaller high-speed blobs or clots. Flare activity appears to vary widely between solar

activity centers. The greatest flare productivity seems to be during the week or 10 days when sunspot activity is at its maximum.

Flares are classified according to size and brightness. In general, the higher the importance classification, the stronger the geophysical effects. Some phenomena associated with solar flares have immediate effects; others have delayed effects (15 minutes to 72 hours after flare).

Solar flare activity produces significant disruptions and phenomena within Earth's atmosphere. During solar flare activity, solar particle streams (solar winds) are emitted and often intercept Earth. These solar particles are composed of electromagnetic radiation which interacts with Earth's ionosphere. This results in several reactions such as: increased ionization (electrically charging neutral particles), photochemical changes (absorption of radiation), atmospheric heating, electrically charged particle motions, and an influx of radiation in a variety

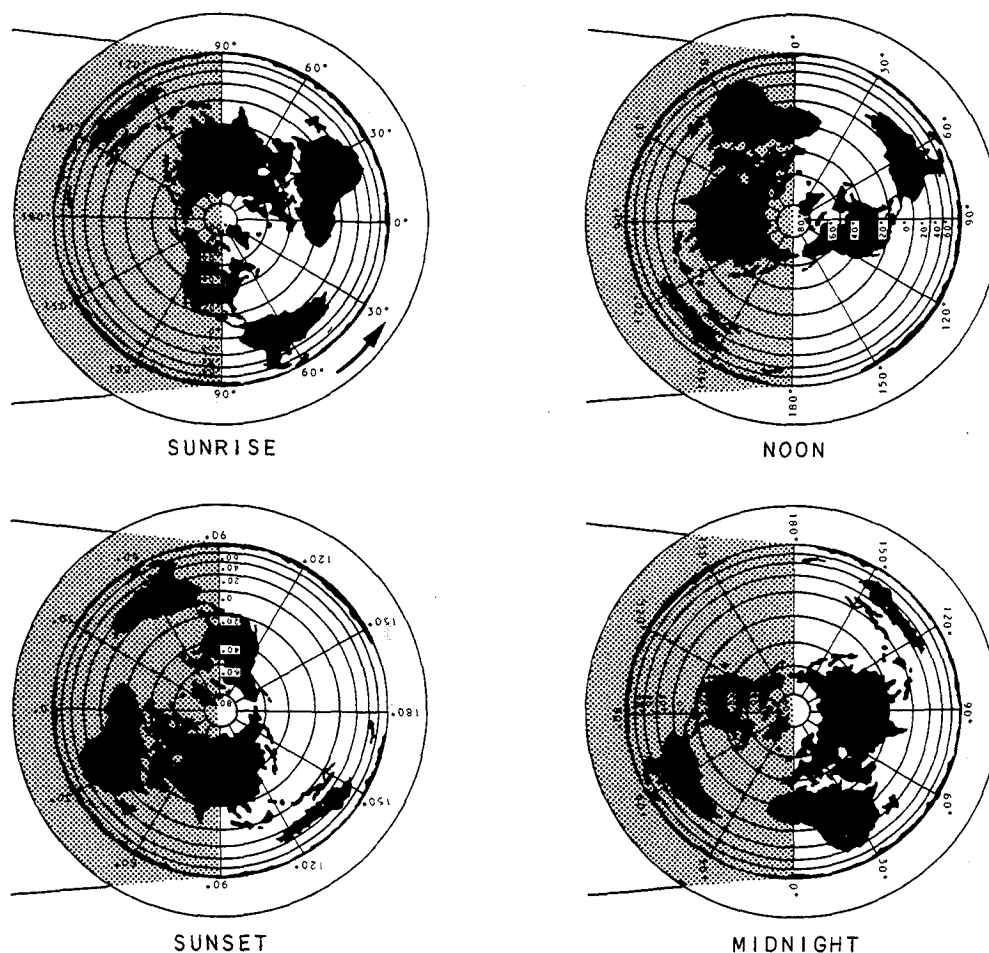


Figure 1-2-3.—Rotation of Earth about its axis (during equinoxes).



of wavelengths and frequencies which include radio and radar frequencies.

Some of the resulting phenomena include the disruption of radio communications and radar detection. This is due to ionization, incoming radio waves, and the motion of charged particles. Satellite orbits can be affected by the atmospheric heating and satellite transmissions may be affected by all of the reactions previously mentioned. Geomagnetic disturbances like the aurora borealis and aurora australis result primarily from the motion of electrically charged particles within the ionosphere.

## EARTH

Of the nine planets in our solar system, Earth is the third nearest to (or from) the Sun. Earth varies in distance from the Sun during the year. The Sun is 94 million miles (150,400,000 km) in summer and 91 million miles (145,600,000 km) in winter.

## Motions

Earth is subject to four motions in its movement through space: rotation about its axis,

revolution around the Sun, precessional motion (a slow conical movement or wobble) of the axis, and the solar motion (the movement of the whole solar system with space). Of the four motions affecting Earth, only two are of any importance to meteorology.

The first motion is rotation. Earth rotates on its axis once every 24 hours. One-half of Earth's surface is therefore facing the Sun at all times. Rotation about Earth's axis takes place in an eastward direction. Thus, the Sun appears to rise in the east and set in the west. (See fig. 1-2-3.)

The second motion of Earth is its revolution around the Sun. The revolution around the Sun and the tilt of Earth on its axis are responsible for our seasons. Earth makes one complete revolution around the Sun in approximately 365 1/4 days. Earth's axis is at an angle of 23 1/2° to its plane of rotation and points in a nearly fixed direction in space toward the North Star (Polaris).

## Solstices and Equinoxes

When Earth is in its summer solstice, as shown for June in figure 1-2-4, the Northern Hemisphere

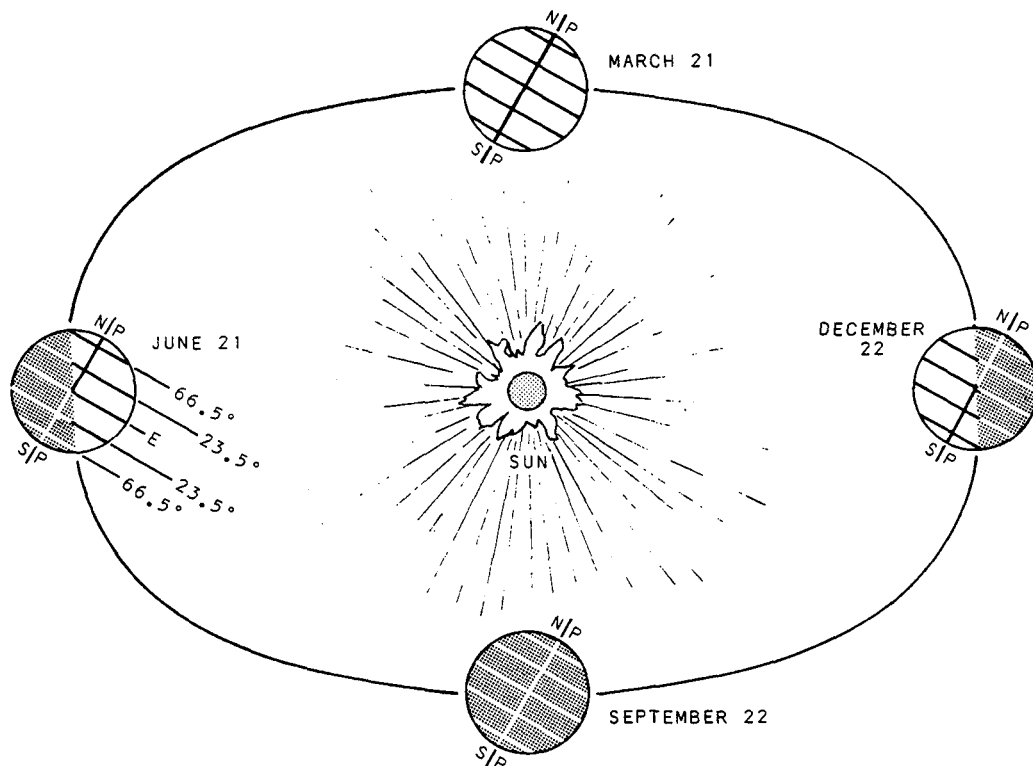


Figure 1-2-4.—Revolution of Earth around the Sun.

is inclined  $23\frac{1}{2}^{\circ}$  TOWARD the Sun. This inclination results in more of the Sun's rays reaching the Northern Hemisphere than the Southern Hemisphere. On or about June 21, direct sunlight covers the area from the North Pole down to latitude  $66\frac{1}{2}^{\circ}\text{N}$  (the ARCTIC CIRCLE). The area between the Arctic Circle and the North Pole is receiving the Sun's rays for 24 hours each day. During this time the most perpendicular rays of the Sun are received at  $23\frac{1}{2}^{\circ}\text{N}$  latitude (the TROPIC OF CANCER). Because the Southern Hemisphere is tilted AWAY from the Sun at this time, the indirect rays of the Sun reach only to  $66\frac{1}{2}^{\circ}\text{S}$  latitude (the ANTARCTIC CIRCLE). Therefore, the area between the Antarctic Circle and the South Pole is in complete darkness. Note carefully the shaded and unshaded area of Earth in figure 1-2-4 for all four positions.

At the time of the equinox in March and again in September, the tilt of Earth's axis is neither toward nor away from the Sun. For these reasons Earth receives an equal amount of the Sun's energy in both the Northern Hemisphere and the Southern Hemisphere. During this time the Sun's rays shine most perpendicularly at the equator.

In December, the situation is exactly reversed from that in June. The Southern Hemisphere now receives more of the Sun's direct rays. The most perpendicular rays of the Sun are received at  $23\frac{1}{2}^{\circ}\text{S}$  latitude (the TROPIC OF CAPRICORN). The southern polar region is now completely in sunshine; the northern polar region is completely in darkness.

Since the revolution of Earth around the Sun is a gradual process, the changes in the area receiving the Sun's rays and the changes in seasons are gradual. However, it is customary and convenient to mark these changes by specific dates and to identify them by specific names. These dates are as follows:

1. March 21. The VERNAL EQUINOX, when Earth's axis is perpendicular to the Sun's rays. Spring begins in the Northern Hemisphere and fall begins in the Southern Hemisphere.

2. June 21. The SUMMER SOLSTICE, when Earth's axis is inclined  $23\frac{1}{2}^{\circ}$  toward the Sun and the Sun has reached its northernmost zenith at the Tropic of Cancer. Summer officially commences in the Northern Hemisphere; winter begins in the Southern Hemisphere.

3. September 22. The AUTUMNAL EQUINOX, when Earth's axis is again perpendicular to the Sun's rays. This date marks the beginning

of fall in the Northern Hemisphere and spring in the Southern Hemisphere. It is also the date, along with March 21, when the Sun reaches its highest position (zenith) directly over the equator.

4. December 22. The WINTER SOLSTICE, when the Sun has reached its southernmost zenith position at the Tropic of Capricorn. It marks the beginning of winter in the Northern Hemisphere and the beginning of summer in the Southern Hemisphere.

In some years, the actual dates of the solstices and the equinoxes vary by a day from the dates given here. This is because the period of revolution is  $365\frac{1}{4}$  days and the calendar year is 365 days except for leap year when it is 366 days.

Because of its  $23\frac{1}{2}^{\circ}$  tilt and its revolution around the Sun, Earth is marked by five natural light (or heat) zones according to the zone's relative position to the Sun's rays. Since the Sun is ALWAYS at its zenith between the Tropic of Cancer and the Tropic of Capricorn, this is the hottest zone. It is called the Equatorial Zone, the Torrid Zone, the Tropical Zone, or simply the Tropics.

The zones between the Tropic of Cancer and the Arctic Circle and between the Tropic of Capricorn and the Antarctic Circle are the Temperate Zones. These zones receive sunshine all year, but less of it in their respective winters and more of it in their respective summers.

The zones between the Arctic Circle and the North Pole and between the Antarctic Circle and the South Pole receive the Sun's rays only for parts of the year. (Directly at the poles there are 6 months of darkness and 6 months of sunshine.) This, naturally, makes them the coldest zones. They are therefore known as the Frigid or Polar Zones.

## RADIATION

The term RADIATION refers to the process by which electromagnetic energy is propagated through space. Radiation moves at the speed of light, which is 186,000 miles per second (297,600 km per second) and travels in straight lines in a vacuum. All of the heat received by Earth is through this process. It is the most important means of heat transfer.

SOLAR RADIATION is defined as the total electromagnetic energy emitted by the Sun. The Sun's surface emits gamma rays, x-rays, ultraviolet, visible light, infrared, heat, and electromagnetic waves. Although the Sun radiates

in all wavelengths, about half of the radiation is visible light with most of the remainder being infrared. (See fig. 1-2-5.)

Energy radiates from a body by wavelengths which vary inversely with the temperature of that body. Therefore, the Sun, with an extremely hot surface temperature, emits short wave radiation. Earth has a much cooler temperature (15°C average) and therefore reradiates the Sun's energy or heat with long wave radiation.

## INSOLATION

Insolation (an acronym for INcoming SOLar radiATION) is the rate at which solar radiation is received by a unit horizontal surface at any point on or above the surface of Earth. In this manual, insolation is used when speaking about incoming solar radiation.

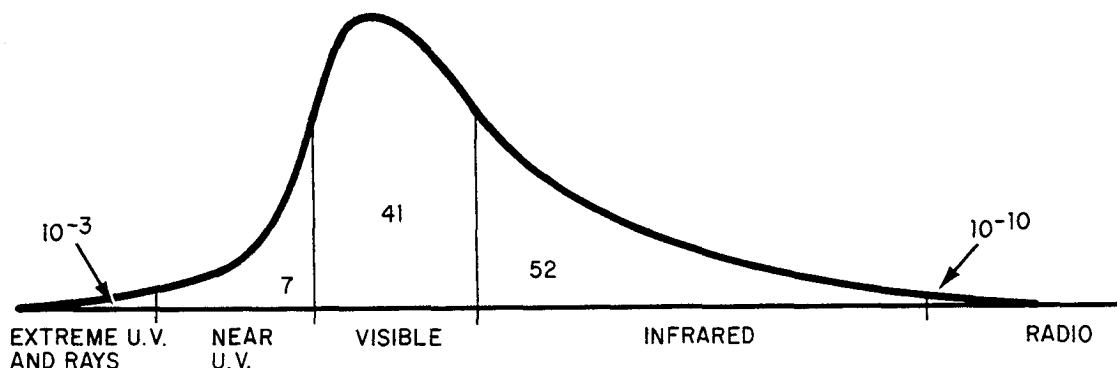
There is a wide variety of differences in the amounts of radiation received over the various portions of Earth's surface. These differences in heating are important and must be measured or otherwise calculated to determine their effect on the weather.

The insolation received at the surface of Earth depends upon the solar constant (the rate at which solar radiation is received outside Earth's atmosphere), the distance from the Sun, inclination of the Sun's rays, and the amount of insolation depleted while passing through the atmosphere. The last two are the important variable factors.

## Depletion of Solar Radiation

If the Sun's radiation was not filtered or depleted in some manner, our planet would soon be too hot for life to exist. We must now consider how the Sun's heat energy is both dispersed and depleted. This is accomplished through dispersion, scattering, reflection, and absorption.

**DISPERSION.**— Earlier it was learned that Earth's axis is inclined at an angle of 23 1/2°. This inclination causes the Sun's rays to be received on the surface of Earth at varying angles of incidence, depending on the position of Earth. When the Sun's rays are not perpendicular to the surface of Earth, the energy becomes DISPERSED or spread out over a greater area



SCHEMATIC DIAGRAM OF THE DISTRIBUTION OF ENERGY IN THE SOLAR SPECTRUM. (NOT TO SCALE). THE NUMBERS ARE PERCENTAGES OF THE SOLAR CONSTANT. THE FIGURE FOR THE RADIO ENERGY IS FOR THE OBSERVED BAND FROM 15 TO 30,000 MHZ.

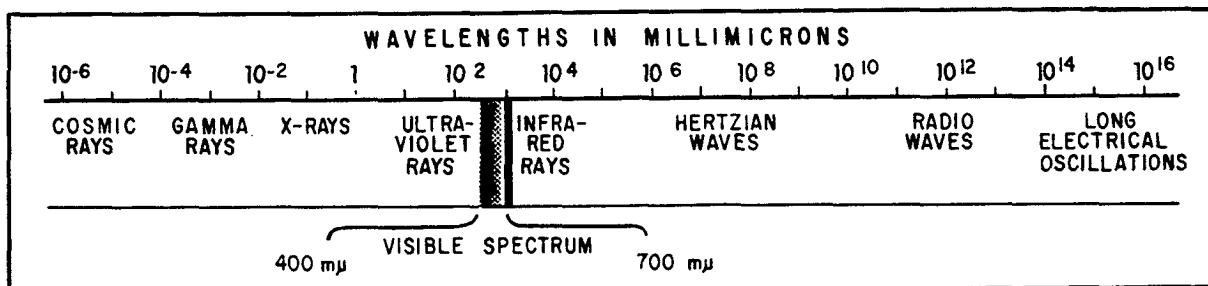


Figure 1-2-5.—Electromagnetic spectrum.

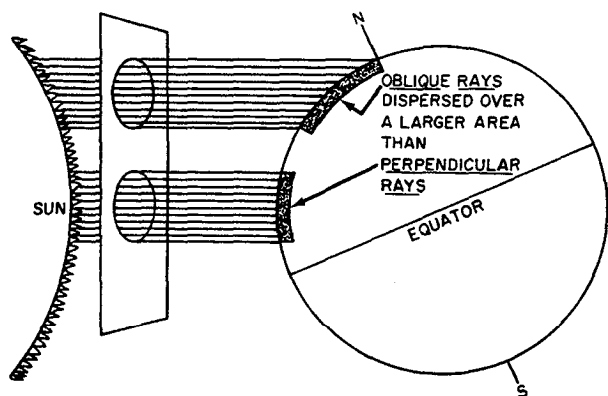


Figure 1-2-6.-Dispersion of insolation.

(fig. 1-2-6). If the available energy reaching the atmosphere is constant and is dispersed over a greater area, the amount of energy at any given point within the area decreases, and therefore the temperature is lower. Dispersion of insolation in the atmosphere is caused by the rotation of Earth. Dispersion of insolation also takes place with the seasons in all latitudes, but especially in the latitudes of the polar areas.

**SCATTERING.**— About 25 percent of the incoming solar radiation is scattered or diffused by the atmosphere. Scattering is a phenomenon that occurs when solar radiation passes through the air and some of the wavelengths are deflected in all directions by molecules of gases, suspended particles, and water vapor. These suspended particles then act like a prism and produce a variety of colors. Various wavelengths and particle sizes result in complex scattering affects that produce the blue sky. Scattering is also responsible for the red Sun at sunset, varying cloud colors at sunrise and sunset, and a variety of optical phenomena (discussed in Unit 5, Lesson 3).

Scattering always occurs in the atmosphere, but does not always produce dramatic settings. Under certain radiation wavelength and particle size conditions, all that can be seen are white clouds and a whitish haze. This occurs when there is a high moisture content (large particle size) in the air and is called diffuse reflection. About two-thirds of the normally scattered radiation reaches Earth as diffuse sky radiation. Diffuse sky radiation may account for almost 100 percent of the radiation received by polar stations during winter.

**REFLECTION.**— Reflection is the process whereby a surface turns a portion of the incident

radiation back into the medium through which the radiation came.

Some insolation is reflected by a substance. This means that the electromagnetic waves simply bounce back into space. Earth reflects an average of 36 percent of the insolation. The percent of reflectivity of all wavelengths on a surface is known as its **ALBEDO**. Earth's average albedo is from 36 to 43 percent. That is, Earth reflects 36 to 43 percent of insolation back into space. In calculating the albedo of Earth, the assumption is made that the average cloudiness over Earth is 52 percent.

All surfaces do not have the same degree of reflectivity; consequently, they do not have the same albedo. Some examples are as follows:

1. Upper surfaces of clouds reflect from 40 to 80 percent, with an average of about 55 percent.
2. Snow surfaces reflect over 80 percent of incoming sunlight for cold, fresh snow and as low as 50 percent for old, dirty snow.
3. Land surfaces reflect from 5 percent of incoming sunlight for dark forests to 30 percent for dry land.
4. Water surfaces (smooth) reflect from 2 percent, when the Sun is directly overhead, to 100 percent when, the Sun is very low on the horizon. This increase is not linear. When the Sun is more than 25° above the horizon, the albedo is less than 10 percent. In general, the albedo of water is quite low.

When Earth as a whole is considered, cloud surfaces are most important in determining Earth's albedo.

**ABSORPTION.**— Earth and its atmosphere absorb about 64 percent of the insolation. Land and water surfaces of Earth absorb 51 percent of this insolation. The remaining 13 percent is directly absorbed by ozone, carbon dioxide, and water vapor. These gases absorb the insolation at certain wavelengths. For example, ozone absorbs only a small percentage of the insolation. The portion or type the ozone does absorb is critical since it reduces ultraviolet radiation to a level where animal life can safely exist. The most important absorption occurs with carbon dioxide and water vapor which absorb strongly over a broader wavelength band. Clouds are by far the most important absorbers of radiation at essentially all wavelengths. In sunlight, clouds reflect a high percentage of the incident solar radiation and account for most of the brightness of Earth as seen from space.

There are regions, such as areas of clear skies, where carbon dioxide and water vapor are at a minimum and so is absorption. These areas are called atmospheric windows and allow insolation to pass through the atmosphere relatively unimpeded.

### Greenhouse Effect

The atmosphere conserves the heat energy of Earth because it absorbs radiation selectively. Most of the solar radiation in clear skies is transmitted to Earth's surface, but a large part of the outgoing terrestrial radiation is absorbed and reradiated back to the surface. This is called the GREENHOUSE effect. A greenhouse permits most of the short-wave solar radiation to pass through the glass roof and sides, and to be absorbed by the floor, ground or plants inside. These objects reradiate energy at their temperatures of about 300°K, which is a higher temperature than the energy that was initially

received. The glass absorbs the energy at these wavelengths and sends part of it back into the greenhouse, causing the inside of the structure to become warmer than the outside. The atmosphere acts similarly, transmitting and absorbing in somewhat the same way as the glass. If the greenhouse effect did not exist, Earth's temperature would be 35°C cooler than the 15°C average temperature we now enjoy, because the insolation would be reradiated back to space.

Of course, the atmosphere is not a contained space like a greenhouse because there are heat transport mechanisms such as winds, vertical currents, and mixing with surrounding and adjacent cooler air.

### RADIATION (HEAT) BALANCE IN THE ATMOSPHERE

The Sun radiates energy to Earth, Earth radiates energy back to space, and the atmosphere radiates energy also. As is shown in figure 1-2-7,

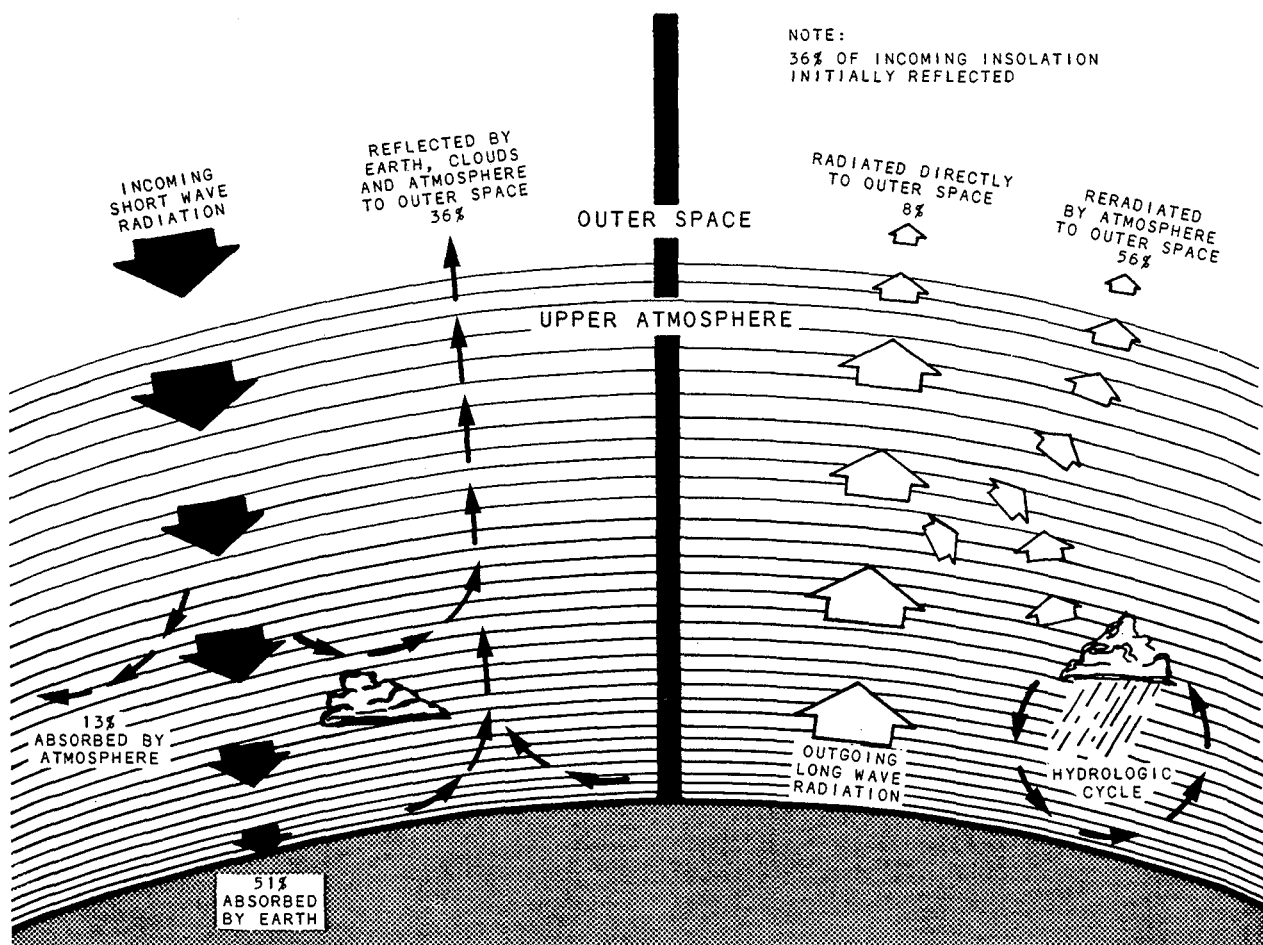


Figure 1-2-7.—Radiation balance in the atmosphere.

a balance is maintained between incoming and outgoing radiation. This section of the lesson explains the various radiation processes involved in maintaining this critical balance and the effects produced in the atmosphere.

We have learned that an object reradiates energy at a higher temperature. Therefore, the more the Sun heats Earth, the greater the amount of heat energy Earth reradiates. If this rate of heat loss/gain did not balance, Earth would become continuously colder or warmer.

### Terrestrial (Earth) Radiation

Radiation emitted by Earth is almost entirely long-wave radiation. Most of the terrestrial radiation is absorbed by the water vapor in the atmosphere and some by other gases (about 8 percent is radiated directly to outer space). This radiant energy is reradiated in the atmosphere horizontally and vertically. Horizontal flux (flow or transport) of energy need not be considered due to a lack of horizontal temperature differences. The vertical, upward or downward, flux is of extreme significance.

Some of this radiation is carried aloft by convection and turbulence. Water vapor, undergoing the condensation-precipitation-evaporation cycle (hydrological cycle), carries the remainder into the atmosphere.

### Atmospheric Radiation

The atmosphere reradiates to outer space most of the terrestrial radiation (about 43 percent) and insolation (about 13 percent) that it has absorbed. Some of this reradiation is emitted earthward and is known as COUNTERRADIATION. This radiation is of great importance in the greenhouse effect.

### Heat Balance and Transfer in the Atmosphere

Earth does not receive equal radiation at all points as was shown in figure 1-2-4. The east-west rotation of Earth provides equal exposure to sunlight but latitude and dispersion do affect the amount of incident radiation received. The poles receive far less incident radiation than the equator. This uneven heating is called differential insolation.

Due to this differential insolation the tropical atmosphere is constantly being supplied heat and

the temperature of the air is thus higher than in areas poleward. Because of the expansion of warm air, this column of air is much thicker and lighter than over the poles. At the poles Earth receives little insolation and the column of air is less thick and heavier. This differential in insolation sets up a circulation that transports warm air from the Tropics poleward aloft and cold air from the poles equatorward on the surface. (See fig. 1-2-8.) Modifications to this general circulation are discussed in detail in Unit 3.

### Summary

This is the account of the TOTAL radiation. Some of the radiation makes several trips, being absorbed, reflected, or reradiated by Earth or the atmosphere. Insolation comes into the atmosphere and all of it is reradiated. How many trips it makes while in our atmosphere does not matter. The direct absorption of radiation by Earth and the atmosphere and the reradiations into space balance. If the BALANCE did not exist, Earth and its atmosphere, over a period of time, would steadily gain or lose heat.

Although radiation is considered the most important means of heat transfer, it is not the only method. There are others such as conduction, convection, and advection that also play an important part in meteorological processes. These will be discussed in more detail later in this unit.

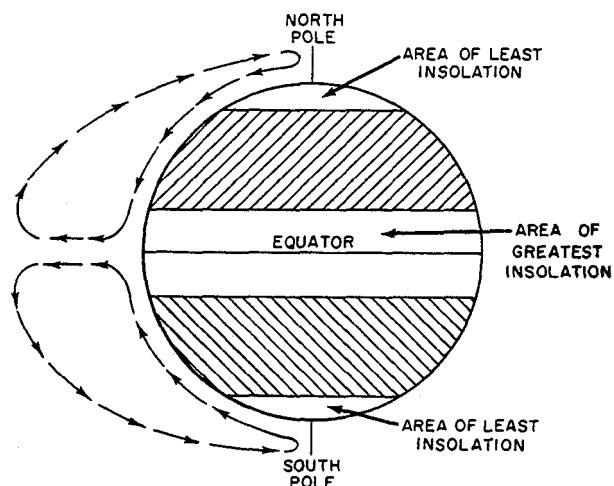


Figure 1-2-8.—Beginning of a circulation.

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## UNIT 1—LESSON 3

# PRESSURE

### OVERVIEW

Describe how pressure is measured and determine how the atmosphere is affected by pressure.

### OUTLINE

Definition

Standards of Measurement

Standard Atmosphere

Vertical Distribution

Pascal's Law

---

### PRESSURE

Pressure is one of the most important parameters in meteorology. A knowledge of the distribution of air and the resultant variations in air pressure over the earth is vital in understanding Earth's fascinating weather patterns.

Pressure is force, and force is related to acceleration and mass by Newton's second law. This law states that acceleration of a body is directly proportional to the force exerted on the body and inversely proportional to the mass of that body. It may be expressed as

$$a = \frac{F}{m} \text{ or } F = ma$$

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**Learning Objective: Describe how pressure is measured and determine how the atmosphere is affected by pressure.**

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where "a" is the acceleration, "F" is the force exerted, and "m" is the mass of the body. This is probably the most important equation in the mechanics of physics dealing with force and motion.

NOTE: Be sure to use units of mass and not units of weight when applying this equation.

### DEFINITION

Pressure is the force per unit area. Atmospheric pressure is the force per unit area exerted by the atmosphere in any part of the atmospheric envelope. Therefore, the greater the force exerted by the air for any given area, the greater the pressure. Although the pressure varies on a horizontal plane from day to day, the greatest pressure variations are with changes in altitude. Nevertheless, horizontal variations of pressure are ultimately important in meteorology because the variations affect weather conditions.

### STANDARDS OF MEASUREMENT

Atmospheric pressure is normally measured in meteorology by the use of a mercurial or aneroid barometer. Pressure is measured in many different units. One atmosphere of pressure is 29.92 inches of mercury or 1,013.25 millibars. These measurements are made under established standard conditions.

## **STANDARD ATMOSPHERE**

The establishment of a standard atmosphere was necessary to give scientists a yardstick to measure or compare actual pressure with a known standard. In the International Civil Aeronautical Organization (ICAO), the standard atmosphere assumes a mean sea level temperature of 59°F or 15°C and a standard sea level pressure of 1,013.25 millibars or 29.92 inches of mercury. It also has a temperature lapse rate (decrease) of 3.6°F per 1000 feet or 0.65°C per 100 meters up to 11 kilometers and a tropopause and stratosphere temperature of – 56.5°C or – 69.7°F.

## **VERTICAL DISTRIBUTION**

Pressure at any point in a column of water, mercury, or any fluid, depends upon the weight of the column above that point.

Air pressure at any given altitude within the atmosphere is determined by the weight of the atmosphere pressing down from above. Therefore, the pressure decreases with altitude because the weight of the atmosphere decreases.

It has been found that the pressure decreases by half for each 18,000-foot (5,400-meter) increase in altitude. Thus, at 5,400 meters one can expect an average pressure of about 500 millibars and

at 36,000 feet (10,800 meters) a pressure of only 250 millibars, etc. Therefore, it may be concluded that atmospheric pressures are greatest at lower elevations because the total weight of the atmosphere is greatest at these points.

There is a change of pressure whenever either the mass of the atmosphere or the accelerations of the molecules within the atmosphere are changed. Although altitude exerts the dominant control, temperature and moisture alter pressure at any given altitude—especially near Earth's surface where heat and humidity, are most abundant. The pressure variations produced by heat and humidity with heat being the dominant force, are responsible for Earth's winds through the flow of atmospheric mass from an area of higher pressure to an area of lower pressure.

## **PASCAL'S LAW**

Pascal's Law is an important law in atmospheric physics. The law states that fluids (including gases such as Earth's atmosphere) transmit pressure in all directions. Therefore, the pressure of the atmosphere is exerted not only downward on the surface of an object, but also in all directions against a surface that is exposed to the atmosphere.



## UNIT 1—LESSON 4

# TEMPERATURE

### OVERVIEW

Describe how temperature is measured and determine how the atmosphere is affected by temperature.

### OUTLINE

Definition

Temperature Scales

Vertical Distribution

Heat Transfer

---

### TEMPERATURE

One of the most important properties of the atmosphere is its ability to absorb and lose heat. The heating and cooling of the atmosphere exerts a tremendous influence on the processes that determine the weather. Consequently, temperature is one of your principal concerns. It is necessary to know the meaning of temperature, the scales and instruments used in its measurement, and the important temperature values. Procedures for observing temperature were discussed in the AG3 rate training manual.

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**Learning Objective: Describe how temperature is measured and determine how the atmosphere is affected by temperature.**

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### DEFINITION

Temperature may be regarded as a measure of molecular motion. Its intensity is determined from absolute zero (Kelvin scale), the point at which all molecular motion stops. Temperature is the degree of hotness or coldness, or it may be considered as a measure of heat intensity.

### TEMPERATURE SCALES

Long ago it was recognized that uniformity in the measurement of temperature was essential. It would be unwise to rely on such subjective judgments of temperature as cool, cooler, and coolest; therefore, arbitrary scales were devised. Some of them are described in this section. They are Fahrenheit, Celsius, and absolute (Kelvin) scales. These are the scales used by the meteorological services of all the countries in the world. Table 1-4-1 shows a temperature conversion scale for Celsius, Fahrenheit, and Kelvin.

#### Fahrenheit Scale

The Fahrenheit scale was invented by Gabriel Daniel Fahrenheit about 1710. He was the first to use mercury in a thermometer. The Fahrenheit scale has 180 divisions or degrees between the freezing (32°F) and boiling (212°F) points of water.

#### Celsius Scale

The Celsius scale was devised by Anders Celsius also during the 18th century. This scale has reference points with respect to water of 0°C for freezing and 100°C for boiling.

It should be noted that many publications still refer to the centigrade temperature scale.

Table 1-4-1.—Temperature Conversion Scale

°C	°F <sup>1</sup>	°K	°C	°F <sup>1</sup>	°K
-40	-40.0	233	+10	+50.0	283
-39	-38.0	234	+11	+52.0	284
-38	-36.5	235	+12	+53.5	285
-37	-34.5	236	+13	+55.5	286
-36	-33.0	237	+14	+57.0	287
-35	-31.0	238	+15	+59.0	288
-34	-29.0	239	+16	+61.0	289
-33	-27.5	240	+17	+62.5	290
-32	-25.5	241	+18	+64.5	291
-31	-24.0	242	+19	+66.0	292
-30	-22.0	243	+20	+68.0	293
-29	-20.0	244	+21	+70.0	294
-28	-18.5	245	+22	+71.5	295
-27	-16.5	246	+23	+73.5	296
-26	-15.0	247	+24	+75.0	297
-25	-13.0	248	+25	+77.0	298
-24	-11.0	249	+26	+79.0	299
-23	-09.5	250	+27	+80.5	300
-22	-07.5	251	+28	+82.0	301
-21	-06.0	252	+29	+84.0	302
-20	-04.0	253	+30	+86.0	303
-19	-02.0	254	+31	+88.0	304
-18	-00.5	255	+32	+89.5	305
-17	+01.5	256	+33	+91.5	306
-16	+03.0	257	+34	+93.0	307
-15	+05.0	258	+35	+95.0	308
-14	+07.0	259	+36	+96.5	309
-13	+08.5	260	+37	+98.0	310
-12	+10.5	261	+38	+100.5	311
-11	+12.0	262	+39	+102.0	312
-10	+14.0	263	+40	+104.0	313
-09	+16.0	264	+41	+106.0	314
-08	+17.5	265	+42	+107.5	315
-07	+19.5	266	+43	+109.5	316
-06	+21.0	267	+44	+111.0	317
-05	+23.0	268	+45	+113.0	318
-04	+25.0	269	+46	+115.0	319
-03	+26.5	270	+47	+116.5	320
-02	+28.5	271	+48	+118.5	321
-01	+30.5	272	+49	+120.0	322
00	+32.0	273	+50	+122.0	323
+01	+33.5	274	+51	+124.0	324
+02	+35.5	275	+52	+125.5	325
+03	+37.5	276	+53	+127.5	326
+04	+39.5	277	+54	+129.0	327
+05	+41.0	278	+55	+131.0	328
+06	+43.0	279	+56	+133.0	329
+07	+44.5	280	+57	+134.5	330
+08	+46.5	281	+58	+136.5	331
+09	+48.0	282	+59	+138.0	332
			+60	+140.0	333

<sup>1</sup> Fahrenheit temperatures are rounded to the nearest 0.5 degree. For a more exact conversion, utilize the psychrometric computer or the mathematical method.

Centigrade simply means graduated in 100 increments, and has recently and officially adopted the name of its discoverer, Celsius.

### Absolute Scale (Kelvin)

Another scale in wide use by scientists in many fields is the absolute scale or Kelvin scale. It was developed by Lord Kelvin of England. On this scale the freezing point of water is 273°K and the boiling point of water is 373°K. The absolute zero value is considered to be a point at which theoretically no molecular activity exists. This places the absolute zero at a minus 273° on the Celsius scale, since the degree divisions are equal in size on both scales. The absolute zero value on the Fahrenheit scale falls at minus 459.6°F.

### Scale Conversions

Two scales, Fahrenheit and Celsius, are commonly used. With the Celsius and Fahrenheit scales, it is often necessary to change the temperature value of one scale to that of the other. Generally a temperature conversion table, like table 1-4-1, is used or a temperature computer. If these are not available, you must then use one of the following mathematical methods to convert one scale to another.

### Mathematical Methods

It is important to note that there are 100 divisions between the freezing and boiling points of water on the Celsius scale. There are 180 divisions between the same references on the Fahrenheit scale. Therefore, one degree on the Celsius scale equals nine-fifths degree on the Fahrenheit scale. In converting Fahrenheit values to Celsius values the formula is:

$$C = (F - 32^{\circ}) \frac{5}{9}$$

In converting Celsius values to Fahrenheit values the formula is:

$$F = \frac{9}{5} C + 32^{\circ}$$

One way to remember when to use 9/5 and when to use 5/9 is to keep in mind that the

Fahrenheit scale has more divisions than the Celsius scale. In going from Celsius to Fahrenheit, multiply by the ratio that is larger; in going from Fahrenheit to Celsius, use the smaller ratio.

Another method of converting temperatures from one scale to another is the decimal method. This method uses the ratio 1°C equals 1.8°F. To find Fahrenheit from Celsius, multiply the Celsius value by 1.8 and add 32. To find Celsius from Fahrenheit, subtract 32 from the Fahrenheit and divide the remainder by 1.8.

Examples:

$$1. F = 1.8C + 32$$

Given: 24°C.; Find: °F

$$24 \times 1.8 = 43.2$$

$$43.2 + 32 = 75.2 \text{ or } 75^{\circ}\text{F.}$$

$$2. C = \frac{F - 32}{1.8}$$

Given: 96°F.; Find: °C.

$$96 - 32 = 64$$

$$64 \div 1.8 = 35.5 \text{ or } 36^{\circ}\text{C}$$

To change a Celsius reading to an absolute value, add the Celsius reading to 273° algebraically. For example, to find the absolute value of -35°C, you would add minus 35° to 273°K algebraically. That is, you take 273° and combine -35° so you use the minus ( - ) function to arrive at 238°K.

To change a Fahrenheit reading to an absolute value, first convert the Fahrenheit reading to its equivalent Celsius value, which is then added algebraically to 273°. Consequently, 50°F is equivalent to 283° absolute, arrived at by converting 50°F to 10°C and then adding the Celsius value algebraically to 273°.

### VERTICAL DISTRIBUTION

Earth's atmosphere is divided into layers or zones according to various distinguishing features.

(See fig. 1-4-1.) The temperatures shown here are generally based on the latest "U.S. Extension to the ICAO Standard Atmosphere" and are representative of mid-latitude conditions. The extension shown in the insert is speculative. These divisions are for reference of thermal structure (lapse rates) or other significant features and are not intended to imply that these layers or zones are independent domains. Earth is surrounded by

one atmosphere, not by a number of sub-atmospheres.

### Layers of the Atmosphere

The layers and zones are discussed under two separate classifications. One is the METEOROLOGICAL classification that defines zones according to their significance for the weather.

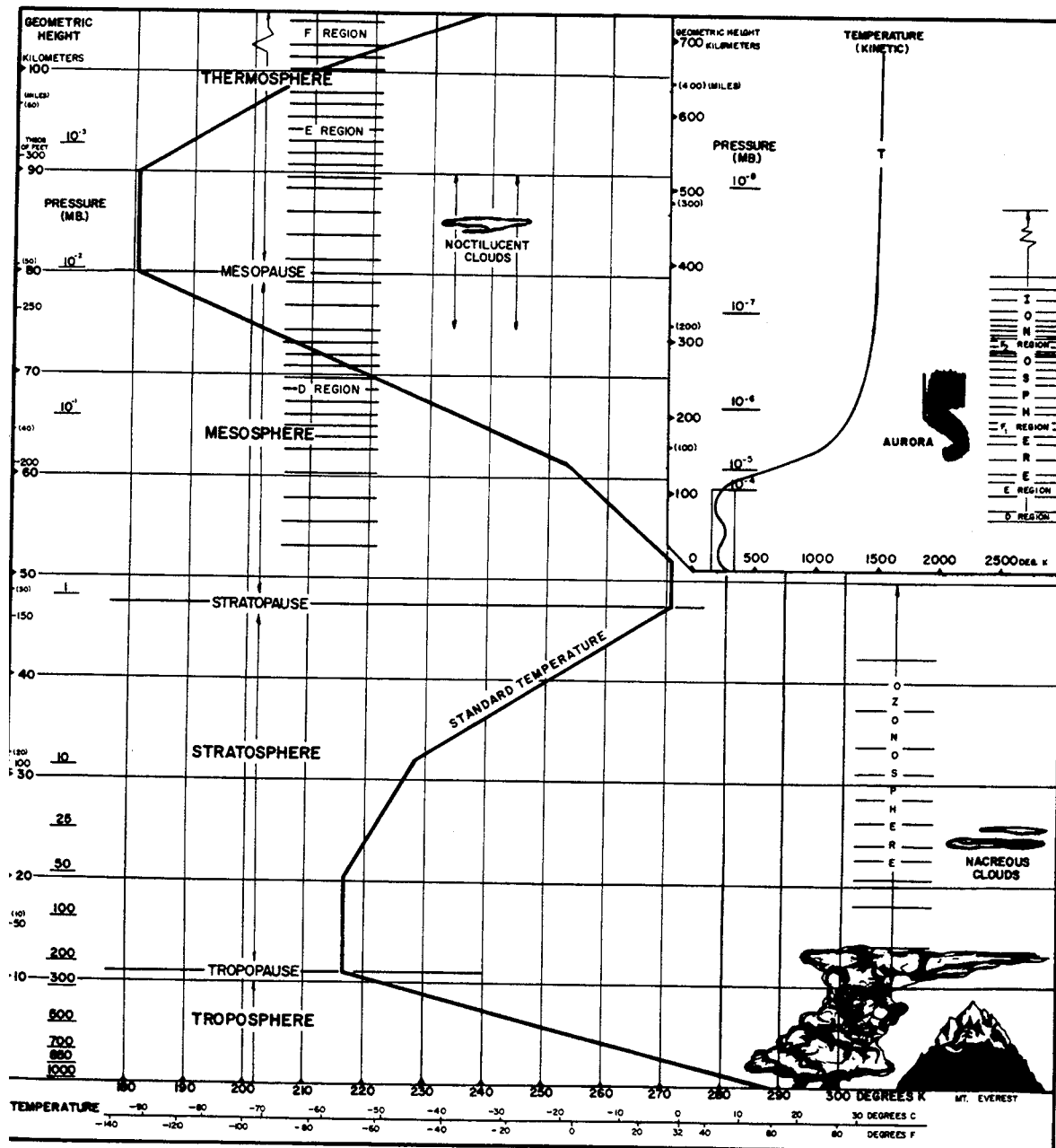


Figure 1-4-1.—Earth's atmosphere.

The other is the ELECTRICAL classification that defines zones according to electrical characteristics of gases of the atmosphere.

**METEOROLOGICAL CLASSIFICATION.**— In the meteorological classification (commencing with Earth's surface and proceeding upward) we have the troposphere, tropopause, stratosphere, stratopause, mesosphere, mesopause, thermosphere, and the exosphere. These classifications are based on temperature characteristics. (See fig. 1-4-1 for some examples.)

**Troposphere.**— The troposphere is the layer of air enveloping Earth immediately above Earth's surface. It is approximately 5 1/2 miles (29,000 ft or 9 km) thick over the poles, about 7 1/2 miles (40,000 ft or 12.5 km) thick in the mid-latitudes, and about 11 1/2 miles (61,000 ft or 19 km) thick over the Equator. The figures for thickness are average figures; they change somewhat from day to day and from season to season. The troposphere is thicker in summer than in winter and is thicker during the day than during the night. Almost all weather occurs in the troposphere. However, some phenomena such as turbulence, cloudiness (caused by ice crystals), and the occasional severe thunderstorm top occur within the tropopause or stratosphere.

The troposphere is composed of a mixture of several different gases. By volume, the composition of dry air in the troposphere is as follows: 78 percent nitrogen, 21 percent oxygen, nearly 1 percent argon, and about 0.03 percent carbon dioxide. In addition, it contains minute traces of other gases, such as helium, hydrogen, neon, krypton, and others.

The air in the troposphere also contains a variable amount of water vapor. The maximum amount of water vapor that the air can hold depends on the temperature of the air and the pressure. The higher the temperature, the more water vapor it can hold at a given pressure.

The air also contains variable amounts of impurities, such as dust, salt particles, soot, and chemicals. These impurities in the air are important because of their effect on visibility and the part they play in the condensation of water vapor. If the air were absolutely pure, there would be little condensation. These minute particles act as nuclei for the condensation of water vapor. Nuclei which have an affinity for water vapor are called HYDROSCOPIC NUCLEI.

The temperature in the troposphere usually decreases with height, but there may be inversions for relatively thin layers at any level.

**Tropopause.**— The tropopause is a transition layer between the troposphere and the stratosphere. It is not uniformly thick, and it is not continuous from the equator to the poles. In each hemisphere the existence of three distinct tropopauses is generally agreed upon—one in the subtropical latitudes, one in middle latitudes, and one in subpolar latitudes. They overlap each other where they meet.

The tropopause is characterized by little or no increase or decrease in temperature with increasing altitude. The composition of gases is about the same as that for the troposphere. However, water vapor is found only in very minute quantities at the tropopause and above it.

**Stratosphere.**— The stratosphere directly overlies the tropopause and extends to about 30 miles (160,000 ft or 48 kilometers). Temperature varies little with height in the stratosphere through the first 30,000 feet (9,000 meters); however, in the upper portion the temperature increases approximately linearly to values nearly equal to surface temperatures. This increase in temperature through this zone is attributed to the presence of ozone that absorbs incoming ultraviolet radiation.

**Stratopause.**— The stratopause is the top of the stratosphere. It is the zone marking another reversal with increasing altitude (temperature begins to decrease with height).

**Mesosphere.**— The mesosphere is a layer approximately 20 miles (100,000 ft or 32 kilometers) thick directly overlaying the stratopause. The temperature decreases with height.

**Mesopause.**— The mesopause is the thin boundary zone between the mesosphere and the thermosphere. It is marked by a reversal of temperatures; i.e., temperature again increases with altitude.

**Thermosphere.**— The thermosphere, a second region in which the temperature increases with height, extends from the mesopause to the exosphere.

**Exosphere.**— The very outer limit of Earth's atmosphere is regarded as the exosphere. It is the zone in which gas atoms are so widely spaced they

rarely collide with one another and have individual orbits around Earth.

**ELECTRICAL CLASSIFICATION.**— The primary concern with the electrical classification is the effect on communications and radar. The electrical classification outlines three zones—the troposphere, the ozonosphere, and the ionosphere.

**Troposphere.**— The troposphere is important to electrical transmissions because of the immense changes in the density of the atmosphere that occur in this layer. These density changes, caused by differences in heat and moisture, affect the electronic emissions that travel through or in the troposphere. Electrical waves can be bent or refracted when they pass through these different layers and the range and area of communications may be seriously affected.

**Ozonosphere.**— This layer is nearly coincident with the stratosphere. As was discussed earlier in this section, the ozone found in this zone is responsible for the increase in temperature with height in the stratosphere.

**Ionosphere.**— The ionosphere extends from about 40 miles (200,000 ft or 64 kilometers) to an indefinite height. Ionization of air molecules in this zone provides conditions that are favorable for radio propagation. This is because radio waves are sent outward to the ionosphere and the ionized particles reflect the radio waves back to Earth.

## HEAT TRANSFER

The atmosphere is constantly gaining and losing heat. Heat is constantly being transported from one part of the world to another by wind movements. It is due to the inequalities in gain and loss of heat that the air is almost constantly in motion. The motions and heat transformations are directly expressed by wind and weather.

### Methods

In meteorology, one is concerned with four methods of heat transfer. These methods are conduction, convection, advection, and radiation. Heat is transferred from Earth directly to the atmosphere by radiation, conduction, and advection. Heat is transferred within the atmosphere by radiation, conduction, and convection. Advection, a form of convection, is used in a

special manner in meteorology. It is discussed as a separate method of heat transfer. As radiation was discussed earlier in the unit, this section covers conduction, convection, and advection.

**CONDUCTION.**— Conduction is the transfer of heat from warmer to colder matter by contact. Although of secondary importance in heating the atmosphere, it is a means by which air close to the surface of Earth heats during the day and cools during the night.

**CONVECTION.**— Convection is the method of heat transfer in a fluid resulting in the transport and mixing of the properties of that fluid. Visualize a pot of boiling water. The water at the bottom of the pot is heated by conduction. It becomes less dense and rises. Cooler and denser water from the sides and the top of the pot rushes in and replaces the rising water. In time, the water is thoroughly mixed. As long as heat is applied to the pot, the water continues to transfer heat by convection. The transfer of heat by convection in this case applies only to what is happening to the water in the pot. In meteorology, the term convection is normally applied to vertical transport.

Convection occurs regularly in the atmosphere and is responsible for the development of air turbulence. Cumuliform clouds, showers and thunderstorms occur when sufficient moisture is present and strong vertical convection occurs. Vertical transfer of heat in the atmosphere (convection) works in a similar manner. Warmer, less dense air rises and is replaced by descending cooler, denser air, which in turn, acquires heat.

### Specific Heat

The specific heat of a substance shows how many calories of heat it takes to raise the temperature of 1 gram of that substance 1°C. Since it takes 1 calorie to raise the temperature of 1 gram of water 1°C, the specific heat of water is 1. The specific heat of a substance plays a tremendous role in meteorology because it is tied directly to temperature changes. For instance, the specific heat of earth in general is 0.33. This means it takes only 0.33 calorie to raise the temperature of 1 gram of earth 1°C. Stated another way, earth heats and cools three times as fast as water. Therefore, assuming the same amount of energy (calories) is available, water heats (and cools) at a slower rate than land does. The slower rate of heating and cooling of water

is the reason temperature extremes occur over land areas while temperatures over water areas are more consistent.

The specific heat of various land surfaces is also different, though the difference between one land surface and another is not as great as between land and water. Dry sand or bare rock has the lowest specific heat. Forest areas have the highest specific heat. This difference in specific heat is another cause for differences in temperature for areas with different types of surfaces even when they are only a few miles apart; this difference is important in understanding the horizontal transport of heat (advection) on a smaller scale.

**ADVECTION.**— Advection is really a form of convection, but in meteorology it means the transfer of heat or other properties

**HORIZONTALLY.** Convection is the term reserved for the **VERTICAL** transport of heat. In this manual the words convection and advection are used to mean the vertical and horizontal transfer of atmospheric properties, respectively.

Horizontal transfer of heat is achieved by motion of the air from one latitude and/or longitude to another. It is of major importance in the exchange of air between polar and equatorial regions. Since large masses of air are constantly on the move somewhere on Earth's surface and aloft, advection is responsible for transporting more heat from place to place than any other physical motion. Transfer of heat by advection is achieved not only by the transport of warm air, but also by the transport of water vapor that releases heat when condensation occurs.





## UNIT 1—LESSON 5

# MOISTURE

### OVERVIEW

Recognize how moisture affects the atmosphere.

### OUTLINE

Atmosphere Moisture

Water Vapor Characteristics

Terms

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### MOISTURE

More than two-thirds of Earth's surface is covered with water. Water from this extensive source is continually evaporating into the atmosphere, cooling by various processes, condensing, and then falling to the ground again as various forms of precipitation.

The remainder of Earth's surface is composed of solid land of various and vastly different terrain features. Knowledge of terrain differences is very important in analyzing and forecasting weather. The world's terrain varies from large-scale mountain ranges and deserts to minor rolling hills and valleys. Each type of terrain significantly influences local wind flow, moisture availability, and the resulting weather.

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**Learning Objective: Describe how moisture affects the atmosphere.**

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### ATMOSPHERIC MOISTURE

Moisture in the atmosphere is found in three states—solid, liquid, and gaseous. As a solid, it takes the form of snow, hail, ice pellets, frost, ice-crystal clouds, and ice-crystal fog. As a liquid, it is found as rain, drizzle, dew, and as the minute water droplets composing clouds of the middle

and low stages as well as fog. In the gaseous state, water forms as invisible vapor. Vapor is the most important single element in the production of clouds and other visible weather phenomena. The availability of water vapor for the production of precipitation largely determines the ability of a region to support life.

The oceans are the primary source of moisture for the atmosphere, but it is also furnished by lakes, rivers, swamps, moist soil, snow, ice fields, and vegetation. Moisture is introduced into the atmosphere in its gaseous state, and may then be carried great distances by the wind before it is discharged as liquid or solid precipitation.

### WATER VAPOR CHARACTERISTICS

There is a limit to the amount of water vapor that air, at a given temperature, can hold. When this limit is reached, the air is said to be saturated. The higher the air temperature, the more water vapor the air can hold before saturation is reached and condensation occurs. (See fig. 1-5-1.) For approximately every 20°F (11°C) increase in temperature between 0°F and 100°F (–18°C and 38°C), the capacity of a volume of air to hold water vapor is about doubled. Unsaturated air, containing a given amount of water vapor, becomes saturated if its temperature decreases sufficiently; further cooling forces some of the water vapor to condense as fog, clouds, or precipitation.

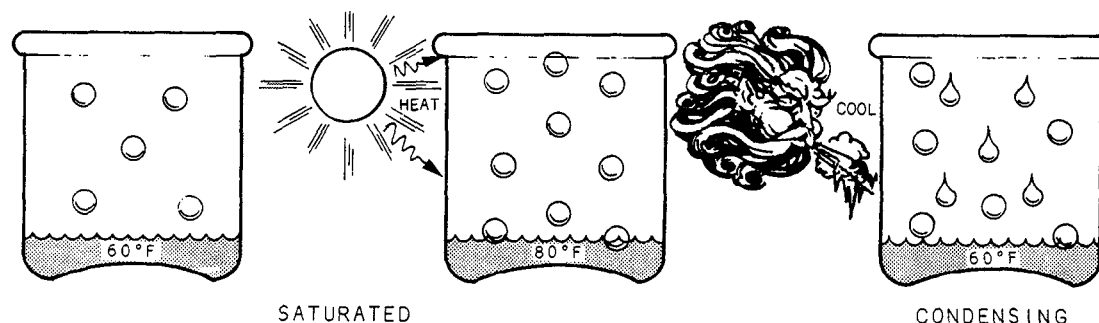


Figure 1-5-1.—Saturation of air depends on its temperature.

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The quantity of water vapor needed to produce saturation does not depend on the pressure of other atmospheric gases. At a given temperature, the same amount of water vapor saturates a given volume of air. This is true whether it be on the ground at a pressure of 1000 mb or at an altitude of 17,000 ft (5,100 meters) with only 500 mb pressure, if the temperature is the same. Since density decreases with altitude, a given volume of air contains less mass (grams) at 5,100 meters than at the surface. In a saturated volume, there would be more water vapor per gram of air at this altitude than at the surface.

### Temperature

Although the quantity of water vapor in a saturated volume of atmosphere is independent of the air pressure, IT DOES DEPEND ON THE TEMPERATURE. The higher the temperature, the greater the tendency for liquid water to turn into vapor. At a higher temperature, therefore, more vapor must be injected into a given volume before the saturated state is reached and dew or fog forms. On the other hand, cooling a saturated volume of air forces some of the vapor to condense and the quantity of vapor in the volume to diminish.

### Condensation

Condensation occurs if moisture is added to the air after saturation has been reached, or if cooling of the air reduces the temperature below the saturation point. As shown in figure 1-5-2, the most frequent cause of condensation is cooling of the air and often results when; (a) air moves over a colder surface, (b) air is lifted (cooled by expansion), or when (c) air near the ground is

cooled at night as a result of radiational cooling.

### Pressure (Dalton's Law)

The laws relative to the pressure of a mixture of gases were formulated by the English physicist, John Dalton. One of the laws states that the partial pressures of two or more mixed gases (or vapors) are the same as if each filled the space alone. The other law states that the total pressure is the sum of all the partial pressures of gases and vapors present in an enclosure.

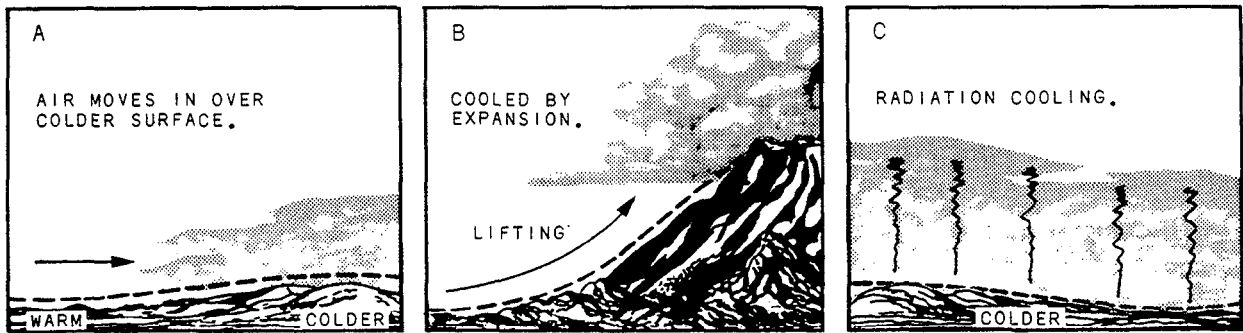
For instance, water vapor in the atmosphere is independent of the presence of other gases. The vapor pressure is independent of the pressure of the dry gases in the atmosphere and vice versa. However, the total atmospheric pressure is found by adding all the pressures—those of the dry air and the water vapor.

### TERMS

The actual amount of water vapor contained in the air is usually less than the saturation amount. The amount of water vapor in the air is expressed in several different methods. Some of these principal methods are described in the following portion of this section.

### Relative Humidity

Although the major portion of the atmosphere is not saturated, for weather analysis it is desirable to be able to say how near it is to being saturated. This relationship is expressed as relative humidity. The relative humidity of a volume of air is the ratio (in percent) between the water vapor actually present and the water vapor necessary for



305.30

Figure 1-5-2.—Causes of condensation.

saturation at a given temperature. When the air contains all of the water vapor possible for it to hold at its temperature, the relative humidity is 100 percent. (See fig. 1-5-3.) A relative humidity of 50 percent indicates that the air contains half of the water vapor that it is capable of holding at its temperature.

Relative humidity is also defined as the ratio (expressed in percent) of the observed vapor pressure to that required for saturation at the same temperature and pressure.

Relative humidity shows the degree of saturation, but it gives no clue to the actual amount of water vapor in the air. Thus, other expressions of humidity are useful.

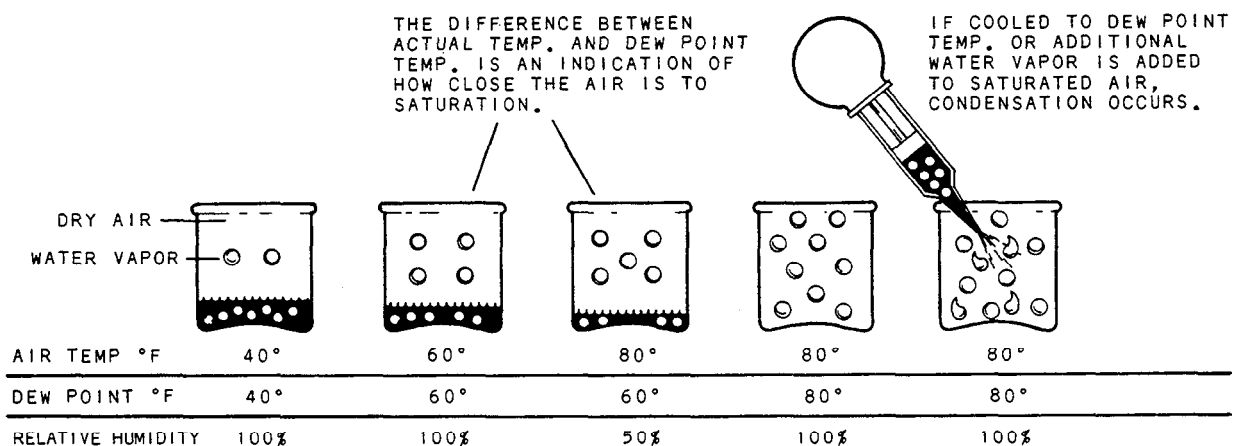
### Absolute Humidity

The mass of water vapor present per unit volume of space, usually expressed in grams per

cubic meter, is known as absolute humidity. It may be thought of as the density of the water vapor.

### Specific Humidity

Humidity may be expressed as the mass of water vapor contained in a unit mass of air (dry air plus the water vapor). It can also be expressed as the ratio of the density of the water vapor to the density of the air (MIXTURE OF DRY AIR AND WATER VAPOR). This is called the specific humidity and is expressed in grams per gram or in grams per kilogram. This value depends upon the measurement of mass, and mass does not change with temperature and pressure. The specific humidity of a parcel of air remains constant unless water vapor is added to or taken from the parcel. For this reason, air that is



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Figure 1-5-3.—Relative humidity and dewpoint.

unsaturated may move from place to place or from level to level, and its specific humidity remains the same as long as no water vapor is added or removed. However, if the air is saturated and cooled, some of the water vapor must condense; consequently, the specific humidity (which reflects only the water vapor) decreases. If saturated air is heated, its specific humidity remains unchanged unless water vapor is added to it. In this case the specific humidity increases. The maximum specific humidity that a parcel can have occurs at saturation and depends upon both the temperature and the pressure. Since warm air can hold more water vapor than cold air at constant pressure, the saturation specific humidity at high temperatures is greater than at low temperatures. Also, since moist air is less dense than dry air at constant temperature, a parcel of air has a greater specific humidity at saturation if the pressure is low than when the pressure is high.

### Mixing Ratio

The mixing ratio is defined as the ratio of the mass of water vapor to the mass of DRY AIR and is expressed in grams per gram or in grams per kilogram. It differs from specific humidity only in that it is related to the mass of dry air instead of to the total dry air plus water vapor. It is very nearly equal numerically to specific humidity, but it is always slightly greater. The mixing ratio has the same characteristic properties as the specific humidity. It is conservative (values do not change) for atmospheric processes involving a change in temperature. It is nonconservative for changes involving a gain or loss of water vapor.

Previously it was learned that air at any given temperature can hold only a certain amount of water vapor before it is saturated. The total amount of vapor that air can hold at any given temperature, by weight relationship, is referred to as the saturation mixing ratio. It is useful to note that the following relationship exists between mixing ratio and relative humidity. Relative humidity is equal to the mixing ratio divided by the saturation mixing ratio, multiplied by 100. If any two of the three components in this relationship are known, the third may be determined by simple mathematics.

### Dewpoint

The dewpoint is the temperature that air must be cooled, at constant pressure and constant water vapor content, in order for saturation to occur. The dewpoint is a conservative and very useful element. When atmospheric pressure stays constant, the dewpoint reflects increases and decreases in moisture in the air. It also shows at a glance, under the same conditions, how much cooling of the air is required to condense moisture from the air.

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